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SUMMARY

A block of ice 30.5 cms. square and 2.5 cms. thick was weighed once daily during the winter season of 1968-69. In this manner gains and losses were determined for each diurnal period. From these data sublimation energy gains and losses were computed.

Only daily periods with the following diurnal temperature and humidity conditions were considered in this study: one, days with maximum temperatures of 0°C. or less; two, days with maximum temperatures above 0°C. but with dewpoint temperatures at or above 0°C. during the same period. These criteria were applied to the climatic measurements observed at the same site. It was assumed that only sublimation losses occurred on 31 days and only sublimation gains occurred on 6 days during the 115 day observational period.

The gains and losses in ice block weight that occurred during these 37 daily periods of assumed only sublimation are related to diurnal temperature changes and mean wind flow. Sublimation losses occurred during diurnal periods in increasing temperatures and increasing winds. Sublimation gains occurred during diurnal periods of decreasing temperatures with little or no wind.

Sublimation gains or losses appear to be closely related large scale synoptic weather changes. Large sublimation losses were strongly associated with diurnal periods of strong advection, while sublimation gains were associated when calm conditions and falling temperature trends characteristic of diurnal periods with strong radiation exchange.

INTRODUCTION

Sublimation is the loss of mass in the form of vapor from snow and ice surfaces directly to the atmosphere. The melting or changing to the liquid phase is entirely absent. Subsequently, gains in mass occur when vapor is deposited as a solid in the form of hoar frost or sublimation gain.

In most areas of the world the hydrological balance parameters for any period of time consists of the total precipitation received in all forms minus evaporation, transpiration, ground storage, and runoff. In much of Alaska an additional form of water loss - that of sublimation - must be taken into account in any refined hydrological balance considerations. In fact, the question of sublimation would appear to be an important one in any in-depth consideration of the long term climate hydrological balance in the arctic and subarctic regions of the Earth.

The hydrological balance of a geographical area is of fundamental importance in long range water-use planning. It has practical importance in short range management decisions as well.

EXPERIMENTAL PROCEDURES

A block of ice of known surface area was weighed daily to determine gains or losses resulting from the winter climatic conditions at Palmer, Alaska. These observations began on Nov. 30, 1968 and ended on March 24, 1969. The usual records of ESSA, EDS cooperative climatic station were observed at the same site. In addition, net and global hemispherical radiation fluxes were recorded, along with daily wind travel 43 cms.above the ice surface and wet and dry bulb temperatures on a once daily basis. These psychrometric readings were made at 1400 hours in order to reflect the highest daily level of absolute humidity.

A block of ice was prepared by placing a galvanized iron pan 30.5 cms. sq. and 2.5 cms. deep, filled with distilled water in a freezer held at -5 C. After freezing and weighing the sample it was exposed by placing it ona horizontal wood platform used in the summer to support a 4' evaporation pan.

The ice block was protected on three sides by the pan leaving the upper surface exposed. At 8:30 A.M. each day the pan containing the ice was removed from the platform, weighed as quickly as possible, and returned to its exposed location.

A totalizing anemometer was utilized to record daily wind movements above the ice block. Dew point temperatures and vapor pressures were determined from the wet and dry bulb temperature readings made with a specially constructed psychrometer.(Branton 1965)

DISCUSSION OF RESULTS

If the total weight loss from the ice block measured continuously during the 115 days of this experiment were assumed to be sublimation, it would be equivalent to 7.3 cms. of water. Since some of this total was due to melting, then evaporating, some way has to be found for estimating only sublimation. Further, the measured weight losses were far from continuous. Weight losses or gains often occurred for one or two days, followed by several days with no losses or gains recorded.

Data recorded on days with possible evaporation were eliminated by the following procedures: First, all days with maximum temperatures above 0°C. were eliminated. Later this procedure was refined to include days with sublimation losses or gains when the maximum temperatures were above 0°C. with dew points at or above 0°C. during the same period with no water accumulation present. By applying these criteria it was estimated that only sublimation losses occurred on 31 days and only sublimation gains occurred on 6 days. The 31 days produced a total seasonal loss of 3.1 cms. of water equivalent sublimation. The 6 days with sublimation gains produced 0.05 cms. (See footnote Tables 1 & 2) These estimates are in reasonable agreement with annual sublimation losses reported by some other investigations.

Investigations that allow one to estimate sublimation on an annual or seasonal basis are very limited, however. Weller (1968) discussed sublimation losses from an ice field in the antarctic during the winter months of April through October. He gives a mean weekly figure of 0.14 cms. On a total seasonal basis his estimates would produce a 4.2 cm. loss. Williams (1963) reports values near 0.05 cms. per day during a 90 day period for observations made on a small lake near Ottawa, Canada. His observations give a seasonal total of approximately 4.5 cms. Both Amback (1960) and LaChapelle (1959) report somewhat smaller rates of sublimation in larger glacier areas than those of Weller and Williams.

Next, a rather lengthy search was made for the possible causes of the discontinuous nature in the occurrence of gains and losses in the ice block weight. In discussing this point Diamond (1953) related that the rates fluxuate greatly from one day to the next similar to that observed in evaporation from a free water surface.

By data inspection it was obvious that sublimational losses and gains at Palmer, Alaska, followed major synoptic weather changes patterns in some way. Further, in all 31 days in which only sublimation losses occurred, the temperature change was upward, and sublimation increased with the increased mean daily wind flow.

During the total 115 day observational season the ice block lost one gram or more due to both sublimation and evaporation on 59 days. The maximum temperature change from the previous day was plus 1°C. or more on 57 of these days.

Sublimation gains were associated with days of temperature drops and decreasing mean daily wind flow. In fact, the greatest sublimation gains occurred during 24 hour periods when no wind flow was recorded. Gains in ice block weight due to hoar frost deposits and dew deposit occurred on 13 days during the 115 day observational period. The maximum temperature dropped 1°C. or more from the previous day in all 13 cases. Attempts were made to correlate calculated vapor pressure gradients, total daily net radiation, and total daily solar radiation. These approaches yielded no significant results. This is not to suggest that an accurate energy balance accounting approach would not yield a better physical explanation of sublimation rates measured in this experiment.

Weight losses or gains due to sublimation only for 31 days during the winter season of 1968-69 were converted to weight loss or gains per square meter and converted to energy gained in Kilo

calories per square meter. An energy factor of 677 calories per gram was used in this sublimation conversion.

Wind data recorded as total m.p.h. for 24 hour periods were converted to mean 24 hour wind flow in meters per second. Temperatures recorded in °F, were converted to °C. The diurnal temperature trend was determined by the change in maximum temperatures from the preceding day. Maximum temperatures were used because this temperature reading was assumed to be of importance in determining whether or not only sublimation occurred. Further, maximums were assumed to be a better measure of macro or synoptic changes that mean djurnal trends. These data are reported in tables 1 and 2. The data were subjected to all possible combinations of single and multiple regression analyses. The most significant results are graphed in figures 1, 2, 3, and 4.

In figure 1 energy requirements for the 31 daily periods assumed to have only sublimation losses are compared with days having temperature increases. The equation for regression relates only a slight trend with a non - significant R - value. In figure 2, energy requirements for sublimation losses for the same 31 daily periods are related to increased mean daily wind

with highly significant results. The multiple correlation of increased wind and temperature added only a slight increase in the correlation value over the single correlation with the wind. (See table 1) But it should be remembered that sublimation losses took place only on days with increased temperature trends. In fact, a simple correlation between wind and the total 115 days in which ice block weight changes occurred gave no significant relationship.

In figure 3 energy requirements for the 6 daily periods assumed to have only sublimation gains are compared with days having temperature decreases. The equation for regression gives a strong predictive trend with a significant R - value near a 10% F. value. It is suggested that this relationship would show an increased level of significance with an increased sample number.

Figure 4 related increased mean daily wind flow to energy requirements of sublimation gains for the same 6 daily periods compared in figure 3. The equation for regression is significant but a negative one, suggesting that hoar frost deposits at ice surface occurs under calm conditions and falling temperatures. Such temperature and wind conditions normally exist

during periods of strong radiation losses.

The relationship between mean wind flow, temperature gradients, and sublimational losses and gains presented in figures 1, 2, 3, and 4 bring up the interesting question of energy source. By comparing amounts of sublimation losses to gains it becomes apparent that there is approximately an order of magnitude difference in energy transfer between these two processes. By assuming that the principle source of energy in sublimation losses is warm air advection and the principle source of energy transfer is radiant loss in the case of sublimation gains, then one must conclude that an order of magnitude difference exists between these two sources.

Weller (1868) calculated the heat budget components for an ice field in Antarctica. He shows daily values of latent heat varying from 10 to 14 gr. cal. per cm^2 per day. Gold and Williams (1961) in discussing a snow field under relatively calm conditions near Ottawa, Canada, state that the sublimation loss was equal to the radiation value minus the heat storage term.

Under conditions of this experimental setup the heat stor-

age term could be considered negligible. Since sublimation gains increased with a decrease in wind (see figure 4) it follows that radiant loss of heat would be the dominant energy root. Under these assumptions the amount of energy gained by the ice block surface during the 6 daily periods with sublimation gains, then loss by radiation varies from approximately 1.5 gr. cal. per cm^2 per day to 7.5 gr. cal. cm^2 per day. These rates of energy transfer to and from an ice surface by radiation is somewhat lower than those of other investigators.

The fact that energy equivalents between sublimation gains and losses are an order of magnitude different in 24 hour period amounts suggests that advected energy transfer completely dominated under these observational conditions. These energy requirements vary from approximately 15 gr. cal. per cm^2 per 24 hour period to over 100.0 gr. cal. cm^2 per 24 hours for several daily periods. (See figure 2) The one value of 1836 gr. cal. per cm^2 on March 5,(Table 1) may not be valid but no justification could be found for eliminating this daily value.

Total net radiation fluxes for the 31 day observational

period were compared for flux trends or changes from one day to the next in much the same manner as temperature trends. Positive flux trends did exist on only 11 of 31 days in which only sublimation losses occured and such positive net radiation value also existed on 19 additional days during the 115 day observational period in which no sublimation gains or losses were recorded. Therefore, one may deduce that positive net radiation flux due to the lack of a radiational sky sink alone cannot predict whether or not sublimational losses will take place.

It is evident from the data reported herein and by others that net annual sublimation losses can be important consideration in climatic hydrological balances. Much of the Earth's surface covered by tundra at high latitudes receives less than 25 cms. of annual precipitation. If 3 to 7 cms. can be lost by sublimation as results in this study, as well as several other investigators, suggest, then sublimation losses must be included in any detailed hydrological balance accounting in arctic and subarctic areas.

An attempt to induce the question of proper hydrolo-

logical balance accounting is illustrated by figures 5, 6, and 7. Figure 5 illustrates the generalized isolines of annual precipitation for Alaska. Isolines of annual evapotranspiration losses are illustrated in figure 6. A tabulated zone of zero hydrological balance is illustrated in figure 7. The accuracy of this zero balance zone as illustrated in figure 7 depends not only on the accurate establishment of the long term mean value for the precipitation isolines and the accurate assessment of net sublimation losses, as well.

Much of Alaska is covered by tundra, which has been ecologically labeled by many as an arctic sub - arid desert. Certainly from a life form viewpoint, the total appearance of the tundra resembles that of the sub - arid cold deserts of the lower latitudes in the world, particularly those in southwestern United States. In those areas of Alaska where the tundra dominates, the climate is sub - arid from an annual water balance viewpoint. (see figure 7) This study only raises the question of how Alaska should be classified as sub - arid if the components of the mean annual hydrological balance were accurately known.

CONCLUSIONS

Warm air advection was the chief energy source for sublimation losses from a block of ice weighed daily at Palmer, Alaska during the 1968 - 1969 winter season. Sublimation gains or hoar frost deposits occurred under some calm conditions of negative radiant flux. There is an order of magnitude difference in these two energy transfer roots as expressed in latent heat gains and losses, with warm air advection being the greater.

Net sublimation can be an important consideration in hydrological balance climatology in the arctic and subarctic areas of the world.

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Legends to Figures

1. Experimental Ice Block Mount, Palmer, Alaska.

2. Sublimation Energy Losses With Increasing Temperature 31 Daily Periods at Palmer, Alaska (Winter 1968-69)

3. Sublimation Energy Losses With Increasing Winds 31 Daily Periods At Palmer, Alaska (Winter 1968-69)

4. Sublimation Energy Gains With Decreasing Temperature 6 Daily Periods at Palmer, Alaska (Winter 1968-69)

5. Sublimation Energy Gains With Increasing Wind 6 Daily Periods at Palmer, Alaska (Winter 1968-69)

6. Inches of Annual Precipitation
   Source: C.I. Branton and C.E. Watson

7. Potential Evapotranspiration, Thornthwaite Method
   Source: J.H. Patric and P.E. Black

8. Annual Water Balance
   Source: C.E. Watson

Table 1.

SUBLIMATION LOSSES DURING A 24-HOUR WARMING PERIOD FOR THE 1968-69 WINTER SEASON - PALMER, ALASKA [1]

Date	Ice Lost (grams/M^2)	Sublimation Energy K-Cal/M^2 (y)	Mean 24-Hr. Wind Flow M/Sec. (x_1)	Temperature Trend (ΔT/24 hrs.) (x_2)
Dec. 18	-21.5	14.6	0.224	+2.2°C.
19	21.5	14.6	0.074	3.9
24	21.5	14.6	0.074	2.2
27	21.5	14.6	0.186	4.4
29	32.3	21.8	0.466	4.4
Jan. 1	365.8	24.8	0.056	5.5
5	807.0	546.0	2.720	12.4
7	204.4	138.0	0.317	1.1
8	828.5	561.0	3.428	2.2
9	1297.2	877.0 [2]	5.533	2.2
10	1297.2	877.0 [2]	6.185	1.1
20	10.8	7.3	0.019	2.2
21	118.4	80.1	0.205	3.3
29	1000.7	677.0	0.224	5.5
30	2991.3	202.5	1.975	4.4
Feb. 2	75.3	51.0	0.075	5.5
5	21.5	14.6	0.913	5.5
6	1764.6	1195.0	2.627	7.8 [3]
7	32.3	21.8	0.093	1.1
9	1248.2	845.0	2.310	6.6
12	860.8	883.0	1.416	1.7
13	1667.8	1129.0	2.310	1.7
16	1614.0	1093.0	2.310	6.6
17	1312.7	889.0	2.049	1.1
18	1560.2	1056.0	1.609	1.1
19	1280.4	867.0	2.608	1.1
24	290.5	197.0	1.509	2.2
Mar. 2	107.6	72.8	0.745	1.1
5	2711.5	1836.0	1.782	3.9 [3]
14	3066.0	58.0	0.671	1.1
16	4497.7	345.0	0.578	1.7 [3]
Total	31,150.7 [4]			

Correlation x_1=0.617 Correlation x_2=0.101 Multiple correlation $x_{1,2}$=0.624
Std. Error x_1 46.1 Std. Error x_2 34.9
F - values
Energy vs wind 7.85 - significant 5%
Energy vs temperature 0.29 not significant
Energy vs wind-temperature 8.93 significant 1%

[1] a warming period is defined as a rise in the maximum temperature from that of the preceding 24 hours.
[2] estimated over two days
[3] maximum temperature above 0°C. during the 24 hour period.
[4] water equivalent sublimation loss for 1968-69 season, 3.12 cms. (1.23 inches)

Table 2.

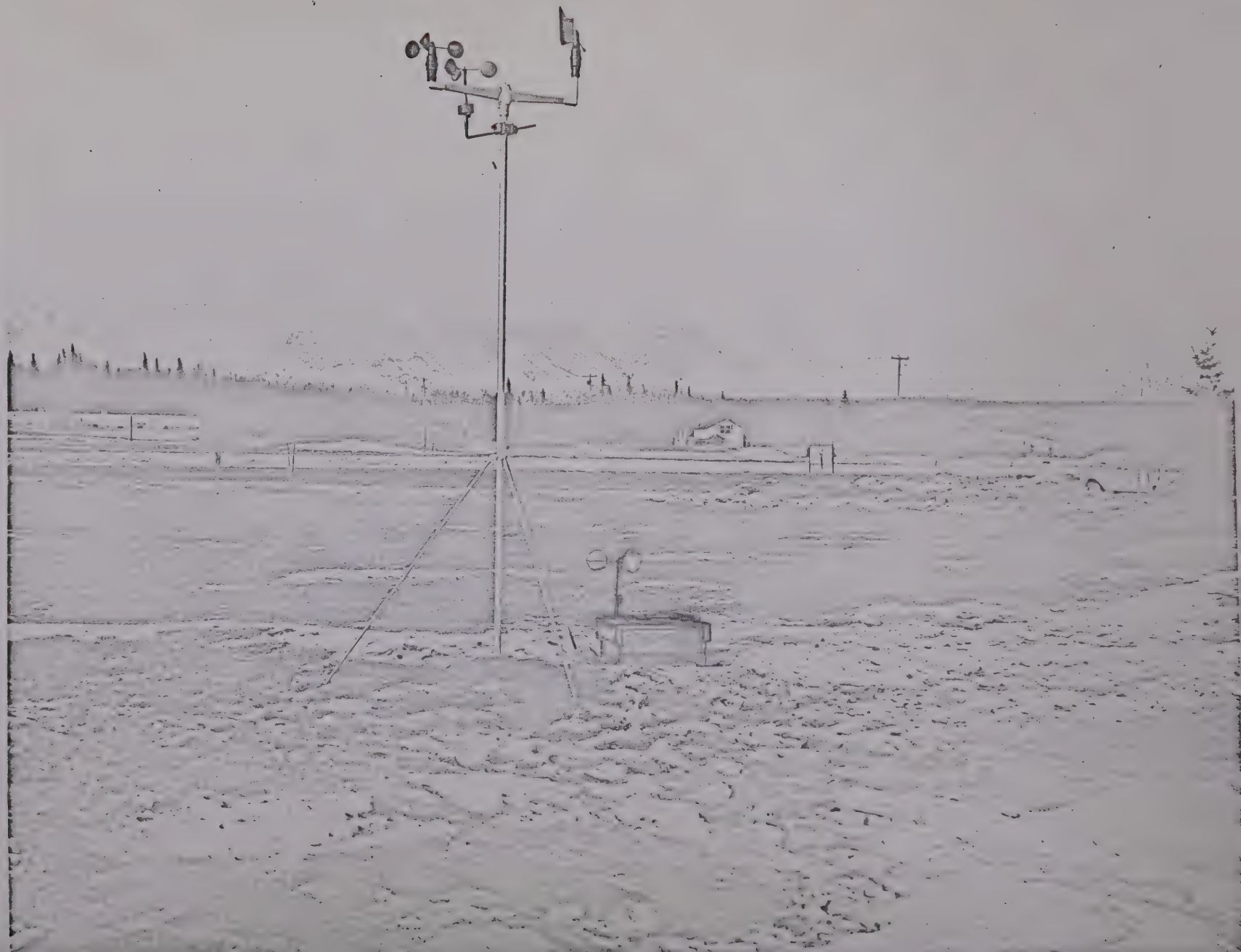
SUBLIMATION GAINS DURING A 24-HOUR COOLING PERIOD FOR THE 1968-69 WINTER SEASON - PALMER, ALASKA [1]

Date	Ice Gain (grams/M^2)	Sublimation Energy (K-Cal/M^2) (y)	Mean 24-Hour Wind Flow (M/sec.) (x_1)	Temperature Trend (ΔT/24 hrs.) (x_2)
Dec. 23	+21.52	14.7	0.074	-1.1°C
25	64.56	43.7	.056	2.2
28	21.52	14.7	.074	3.3
31	53.80	36.4	.019	6.6
Jan. 13	53.80	34.4	.019	2.8
14	107.60	72.9	.019	6.1
Feb. 15	107.60	72.9	.019	6.6
Total	430.40 [2]			

Correlation x_1=0.733
Correlation x_2=0.711
Multiple correlation $x_{1,2}$=0.771
Std. Error x_1 18.0
Std. Error x_2 18.6
F - values
Energy vs wind 5.80, not significant
Energy vs temperature 5.10, not significant
Energy vs wind-temperature 2.92, not significant

[1] a cooling period defined as drop in the maximum temperature from that of the preceding 24 hours

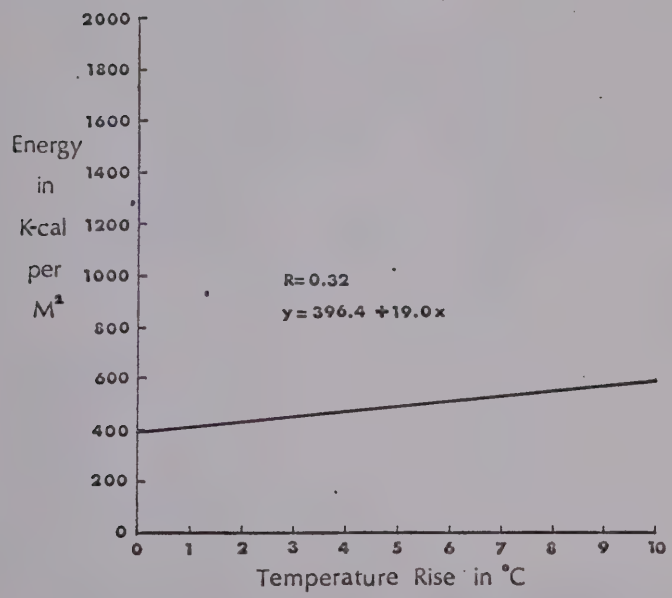
[2] water equivalent sublimation gain for the 1968-69 season, .05 cm.

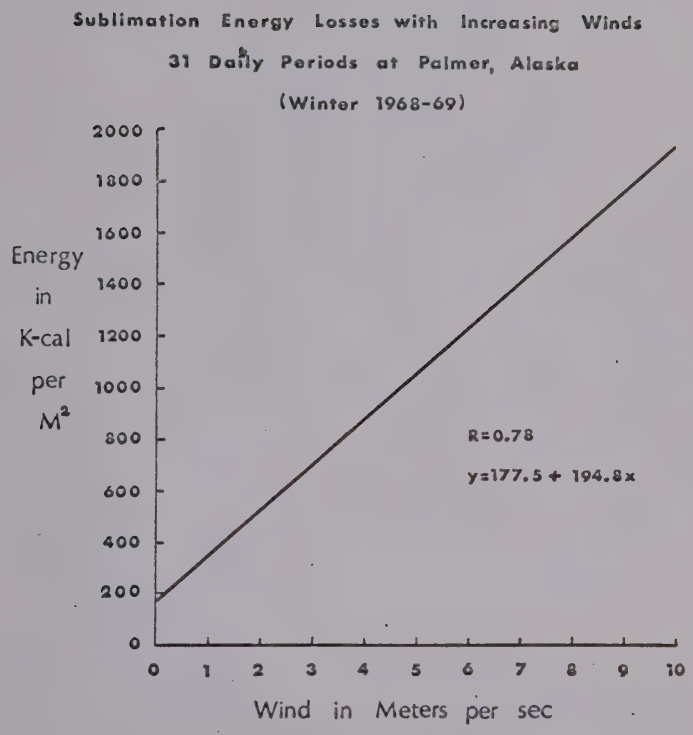


Sublimation Energy Losses with Increasing Temperature

31 Daily Periods at Palmer, Alaska

(Winter 1968-69)

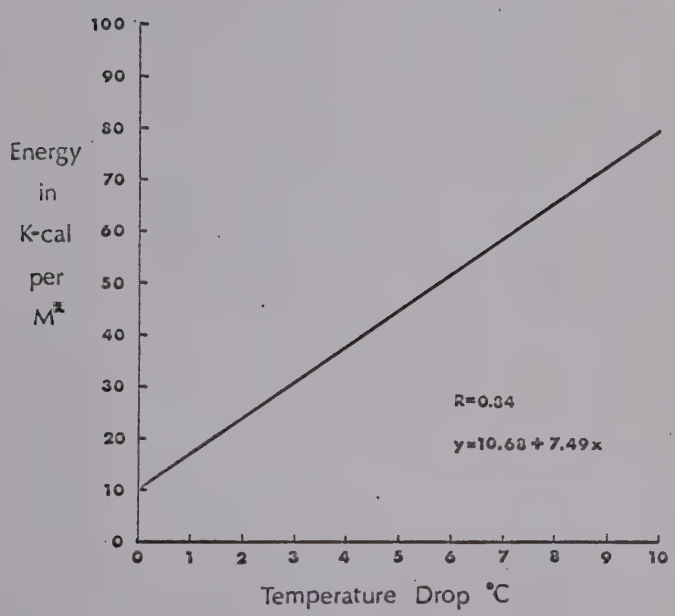



Sublimation Energy Losses with Increasing Winds
31 Daily Periods at Palmer, Alaska
(Winter 1968-69)
Energy in K-cal per M²
2000
1800
1600
1400
1200
1000
800
600
400
200
0
R=0.78
y=177.5 + 194.8x
0 1 2 3 4 5 6 7 8 9 10
Wind in Meters per sec

Sublimation Energy Gains with Decreasing Temperature

6 Daily Periods at Palmer, Alaska

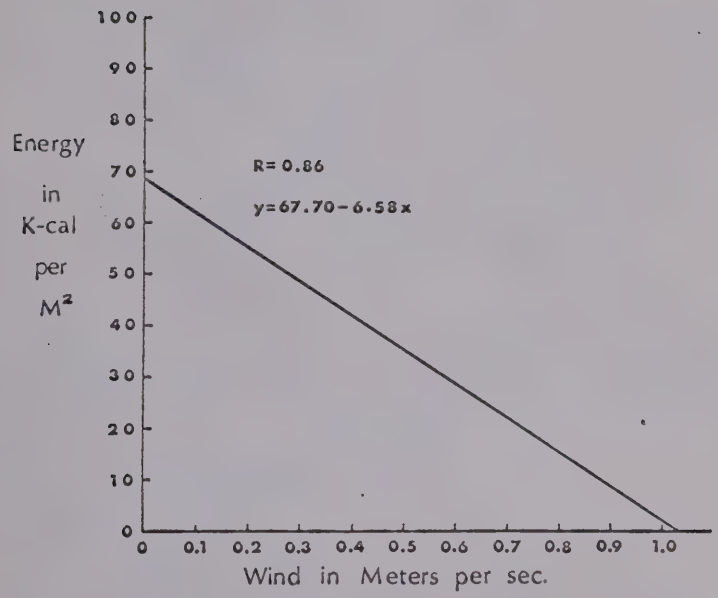
(Winter 1968-69)

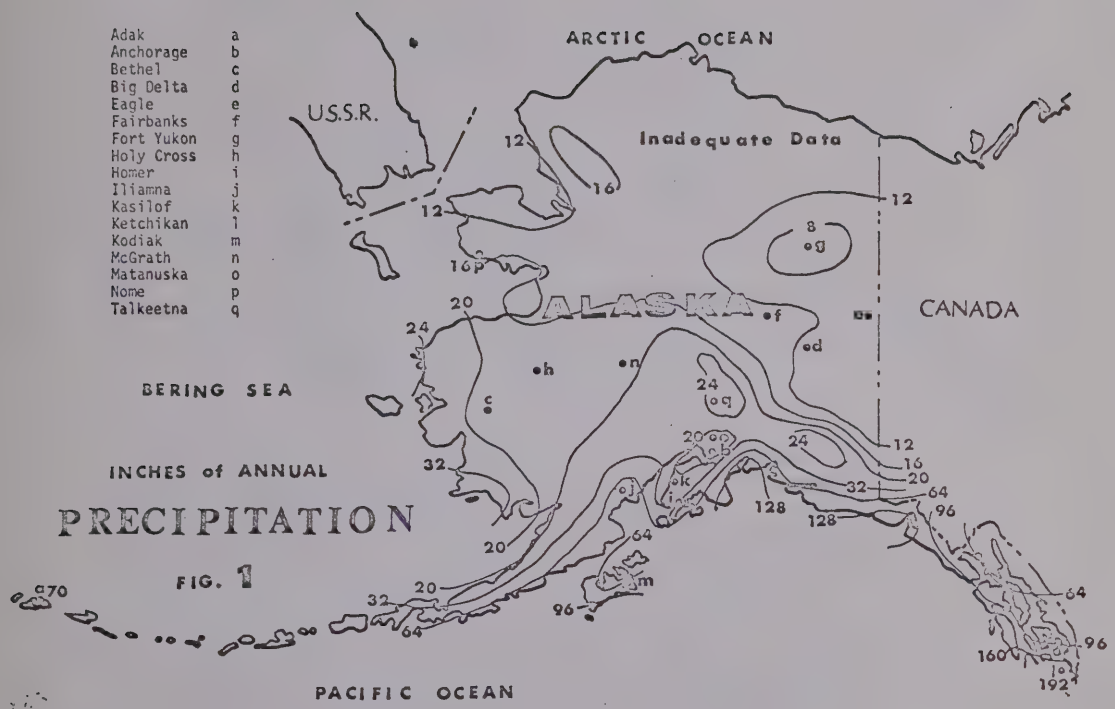


Sublimation Energy Gains with Increasing Wind

6 Daily Periods at Palmer, Alaska

(Winter 1968-69)




Adak a
Anchorage b
Bethel c
Big Delta d
Eagle e
Fairbanks f
Fort Yukon g
Holy Cross h
Homer i
Iliamna j
Kasilof k
Ketchikan l
Kodiak m
McGrath n
Matanuska o
Nome p
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ARCTIC OCEAN
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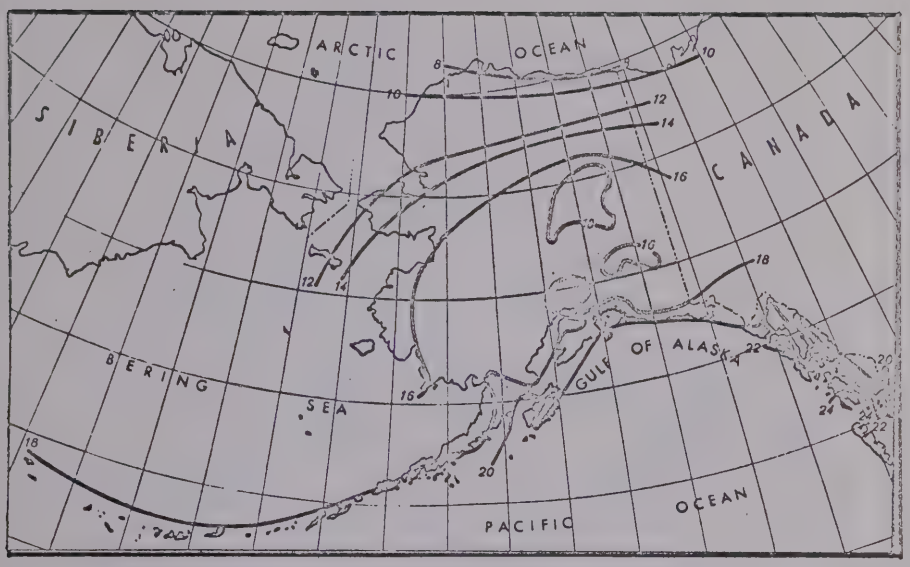
PRECIPITATION

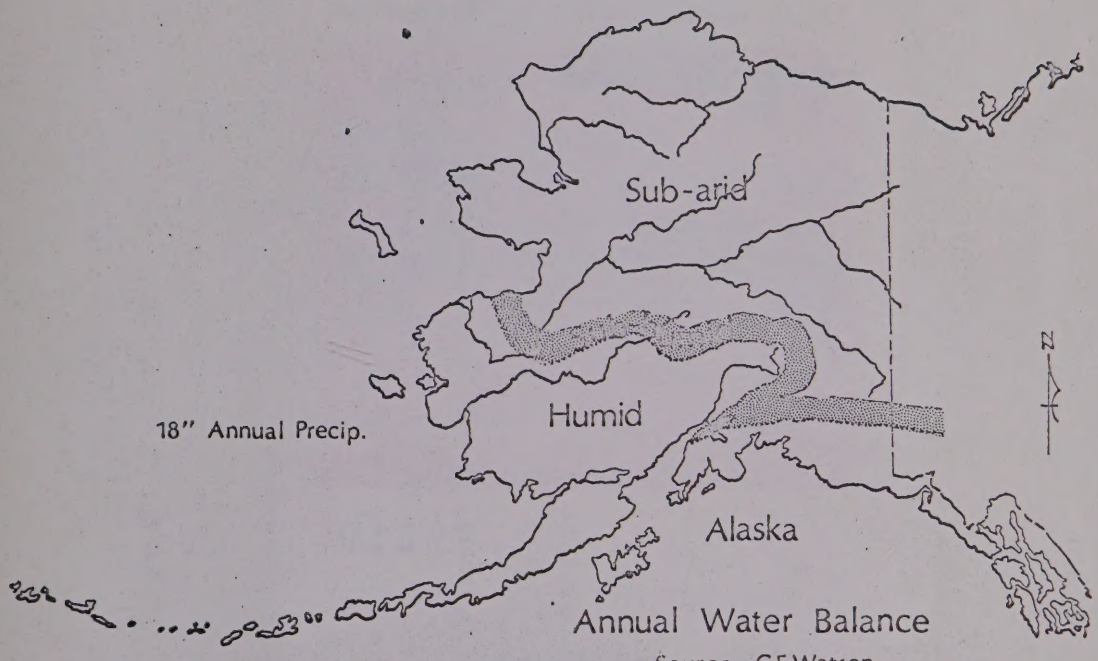
FIG. 1



Potential Evapotranspiration

Thornthwaite Method

Source: J.H. Patric & P.E. Black



Annual Water Balance

Source C.E.Watson

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